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Introduction

As drought struck corn fields through much of southeastern Iowa in 2005, producers were reminded that mycotoxin problems, especially aflatoxins, often follow drought stress. Aflatoxins (produced by the fungi Aspergillus flavus and A. parasiticus) are a chronic problem for corn producers in some areas of the U.S., such as the Texas panhandle and much of the southeastern U.S. In Iowa, widespread aflatoxin problems occurred in 1983 and 1988, but since then there has not been a severe year for aflatoxins across the state. However, parts of Iowa have seen unacceptable levels of aflatoxins several times since 1988, including 1991, 1997, and 2005.

Aflatoxins are the best-recognized group of mycotoxins, but are not the most common mycotoxins in the Corn Belt. Other economically important mycotoxins include the fumonisins (produced primarily by Fusarium verticillioides and F. proliferatum), deoxynivalenol (DON or vomitoxin, a trichothecene mycotoxin), and zearalenone (produced primarily by Fusarium graminearum). Drought stress tends to favor aflatoxins and fumonisins, but not DON and zearalenone. This article will focus on aflatoxins and fumonisins, factors that favor their occurrence, how they are managed, and future prospects for managing levels of these mycotoxins, primarily from a pre-harvest standpoint.

First of all, why are aflatoxins and fumonisins a concern? These toxins, produced by ear rot fungi after they infect corn kernels, are associated with specific detrimental health effects that have been documented in domestic animals and either documented or suspected for humans. These effects have been reviewed in many publications including a recent book (CAST, 2003). Because of these potential impacts on livestock production and human health, corn end-users have established standards, and in some cases government regulatory agencies have established standards, that specify the maximum allowable concentrations of these mycotoxins in corn destined for different uses. When corn exceeds these standards, it impacts the ability of the producer to market the crop at the most advantageous price. The biggest impact in the U.S. has been for corn exceeding 20 ppb (parts per billion) of aflatoxin, the action level established by federal regulations. However, in the future, regulatory activity related to mycotoxins is likely to gain momentum and the aflatoxin situation may be repeated in relation to the presence of other mycotoxins such as those already mentioned.

Factors affecting mycotoxin occurrence

Like all diseases, the occurrence of ear rots is affected by host characteristics, environmental factors, and pathogen characteristics. Mycotoxin production is closely related to disease development in most cases, although there can be exceptions. This creates another layer of complexity that doesn't exist for other plant diseases. Nevertheless, one of the most important factors that determine the level of disease and mycotoxin accumulation is genetic resistance of corn hybrids. In this regard, there has been a great deal of research directed toward both A. flavus and F. verticillioides. In both as extensively as is needed. There have been significant obstacles to incorporating high levels of resistance to these fungi into high-yielding, commercially desirable, adapted hybrids. Even after approximately 20 years of federally funded research through the USDA Aflatoxin Elimination Program, there are no commercial hybrids available with high levels of resistance to A. flavus. Yet hybrids differ significantly in levels of partial resistance, particularly for Fusarium ear rot (Clements et al., 2004). In addition, physical traits of hybrids, such as husk coverage, are related to disease susceptibility. Genetic variability in the pathogen population is a relatively unexplored factor that also may contribute to variability in disease and mycotoxins; competition among fungal strains is an additional, unpredictable influence on mycotoxin levels.

Aflatoxins have long been associated with specific weather conditions, namely drought and heat. Particularly in the Corn Belt, years with abnormally high temperatures and/or low rainfall are predictably higher for aflatoxin risk. Less well understood is the importance of the timing and severity of the drought stress, as well as interactions with soil type and fertility. All of these have been shown to influence aflatoxin levels. These factors may help to explain why aflatoxin levels across southeastern Iowa and western Illinois do not necessarily correlate with season-long drought severity. Aspergillus ear rot severity, A. flavus infection, and elevated aflatoxin levels also have long been associated with kernel injury due to insect feeding, in the field and in storage (Dowd, 1998). Damage to the husks and kernels provides easy access for fungal spores dispersed by air. Corn earworm, European corn borer, southwestern corn borer, and fall armyworm are caterpillar species that have been associated with elevated A. flavus infection. Additionally, several species of sap beetles have been implicated as vectors of A. flavus (CAST, 2003; Dowd, 1998). In tropical areas, other insects are associated with A. flavus infection.

Fusarium ear rot also is influenced by drought stress and is favored by warm temperatures, although not as strikingly as Aspergillus (Miller, 1994). The optimal temperature for F. verticillioides is reported as about 30 C (Marín et al, 1999). Several lines of evidence indicate that drought stress is associated with elevated levels of F. verticillioides infection and fumonisin accumulation in kernels (Miller, 2001). Shelby et al. (1994) showed that, in a group of corn hybrids planted in different U.S. locations, fumonisin levels were inversely correlated with June rainfall. An earlier report from Illinois indicated that Fusarium ear rot was negatively correlated with rainfall during June and July but positively correlated with rainfall during the period from August to October (Koehler, 1959). These results are consistent, in that a dry period before or during grain filling favors more severe Fusarium ear rot and higher levels of fumonisins.

Insect injury is a very important influence on the occurrence of Fusarium ear rot. In addition to the insects implicated in Aspergillus infection, thrips are known to enhance Fusarium ear rot infection. In addition, there may be an interaction between drought stress, insect populations, and Fusarium ear rot and fumonisins. During several years (e.g., 1989, 1997) when drought stress occurred in the central U.S., both fumonisins (Munkvold et al., 1999) and European corn borer populations (Bullock and Nitsi, 2001) were higher than average. Although the hypothesis is difficult to test, annual fluctuations in insect populations are likely to be a significant factor in fumonisin content of corn grain.

Cultural practices for mycotoxin management

Cultural practices designed to reduce mycotoxin contamination of crops have their roots in plant disease epidemiology. The general strategy is to alter the conditions under which the crop is grown so that infection by the offending fungus or fungi is avoided. Tactics employed in this struggle include those used to battle most plant diseases: tillage practices, fertilization practices, crop rotation, plant population, planting date, and irrigation.

Most toxigenic fungi survive in crop residue and managing surface residue through crop rotation or tillage has been investigated as a tactic for mycotoxin reduction. The most recent research has been in relation to head scab of wheat, caused by Fusarium graminearum. This fungus also causes Gibberella ear rot and DON contamination of corn and crop residues are clearly the most important source of inoculum for this host as well (Sutton, 1982). Managing crop residue through rotation or tillage is suggested as a control measure for the disease on corn, but there is little direct evidence for the success of this approach. Studies on the survival of A. flavus and Fusarium species that cause Fusarium ear rot (F. verticillioides, F. subglutinans, and F. proliferatum) suggest that tillage and crop rotation are unlikely to affect these diseases and their mycotoxins. It is likely that airborne spores of F. verticillioides and A. flavus are so common that within-field residue management is not adequate to reduce infection levels or mycotoxin contamination.

Mycotoxin contamination in corn depends on the coincidence of host susceptibility, environmental conditions favorable for infection, and, in some cases, vector activity. Because of the importance of timing in the events leading to infection, a change in planting date can have a significant effect on mycotoxin accumulation. In corn, earlier planting dates in temperate areas generally result in a lower risk, but this effect can be affected greatly by annual fluctuations in weather. Aflatoxin development in corn can be affected by several cultural practices, partially because of the relationship between drought stress and susceptibility to A. flavus and aflatoxin accumulation. Cultural practices that tend to expose plants to greater drought stress will lead to higher levels of aflatoxins. The combined effects of several cultural practices on aflatoxin development in corn have been investigated. Earlier planting and harvest, along with irrigation or deep tillage to alleviate drought stress, all reduced infection and aflatoxin levels. A study conducted in Mexico demonstrated that a combination of cultural practices (early planting, reduced plant population, and irrigation), hybrid selection, and insect control reduced aflatoxin concentrations down to 0 to 6 ng/g, compared to 63 to 167 ng/g in late-planted, non-irrigated corn at a higher plant population without insect control (Rodriguez-del-Bosque, 1996). Elevated aflatoxin levels have been associated with fertility- and weed-related stresses (Lisker and Lillehoj, 1991). Jones and Duncan (1981) reported that a higher rate of nitrogen fertilization consistently resulted in reduced aflatoxin levels.

Many of the cultural practices that may be employed to discourage disease require decisions to be made prior to planting. The need for such measures traditionally has been gauged using informal risk assessment methods, which usually are very imprecise. Quantitative, site-specific risk assessments or predictive models for mycotoxin accumulation could contribute significantly to management efficiency. Efforts in this area are growing. A model has been developed to assess the risk of aflatoxin contamination of pre-harvest corn in the southeastern United States (Widstrom et al, 2000), which takes into account rainfall and other weather inputs, insect populations, corn hybrid, planting date, and other factors, including economic considerations. A mathematical simulation of ear rot development following inoculation with F. graminearum and F. verticillioides was presented by Stewart et al (2002). Although this work did not include a component for prediction of initial infection, it provides a detailed quantitative assessment of environmental influences on post-infection disease development. A recent model uses the effects of insect populations and weather conditions to model the development of fumonisins in corn grown in Argentina and the Philippines (De La Campa et al., 2005). In wheat, a model for the prediction of DON levels has been developed in Ontario (Hooker et al., 2002) and another in Ohio (DeWolf et al., 2001). Most of these modeling efforts represent tactics that will provide an early warning for the risk of unacceptable mycotoxin levels, but depend on within-season weather data. Pre-planting management decisions require stochastic models based on long-term weather forecasts and/or extensive historical data on mycotoxin occurrence. This type of model has not been developed for mycotoxins in corn or other crops.

Management of mycotoxins requires late-season scouting in order to make informed decisions about harvest timing, post-harvest grain handling, storage and marketing. Timing of harvest can have a major impact on the ultimate level of mycotoxin accumulation. In general, earlier harvest results in lower levels of mycotoxins (Jones et al, 1981). While grain dries slowly in the field, moisture content remains high enough to allow continued development and toxin production by fungi that infect kernels pre-harvest. Insects may continue to feed on corn in the field late in the season, enhancing the ability of fungi to attack the kernels. On the other hand, if there is little pre-harvest infection, if insect activity is not a serious problem, and weather conditions are favorable for grain drying, it can be safe to allow field drying to proceed to desirable moisture levels. To assess the need to harvest early, scouting in the field is necessary.

Mycotoxin management through genetic resistance

High levels of genetic resistance to toxigenic fungi in corn have been difficult to achieve. Among the challenges faced are inconsistent, labor-intensive inoculation techniques, lack of major single genes, lack of resistant control genotypes, and the expense of evaluating results, especially mycotoxin levels. But progress has been made. Inbred and hybrid selection during the breeding and testing processes usually eliminate very susceptible genotypes so widely grown hybrids are not excessively susceptible, but unacceptable mycotoxin levels are not uncommon. Partial resistance to Gibberella ear rot was identified in several studies and both dominant and additive genetic effects were reported. At least one major gene for resistance to Gibberella ear rot has been identified (Reid et al, 1994); corn inbreds and hybrids expressing this gene have very low severity of Gibberella ear rot and their grain also has greatly reduced levels of deoxynivalenol (DON) compared to susceptible genotypes. For this pathogen, resistance to infection through the silks and resistance to spread of the fungus among the kernels are under separate genetic control. Major-gene resistance is not yet widely used in commercial dent corn or sweet corn hybrids, but currently used hybrids express partial resistance to Gibberella ear rot.

Genetic resistance to Aspergillus infection and aflatoxin accumulation has been studied extensively and reported in the literature. During the 1970s, hybrids were evaluated for differences in aflatoxin accumulation and sources of resistance were reported by the mid- to late-1980s. Studies of inheritance of resistance also have been conducted since the 1980s and still continue (Campbell and White, 1995; Walker and White, 2001). Inoculation techniques have been a chronic issue affecting the results of these studies and many methods have been reported. Currently there are several well-characterized sources for resistance to A. flavus infection or aflatoxin production (Brown et al, 1999). Inheritance studies have shown additive and dominant gene activity in crosses between resistant and susceptible inbreds (Campbell and White, 1995). Identifying and characterizing sources of resistance is a very active area of research; several sources, such as Tex6 and GT-MAS: gk, Oh516, LB31, and MI82, have been well studied, and new sources continue to be identified. Utilization of germplasm identified in these studies has been hampered by its lack of adaptation to the Corn Belt (Campbell and White, 1995) and difficulties in incorporating polygenic resistance into elite germplasm. Currently, corn hybrids with improved resistance to A. flavus and aflatoxins are being used, but the level of resistance is not yet adequate to prevent unacceptable aflatoxin concentrations in some fields. Active breeding programs are under way in the public sector.

Research on resistance to Fusarium ear rot has not been reported in the literature as thoroughly as for A. flavus and Gibberella ear rot. Sources of resistance to Fusarium ear rot have been identified, but they are polygenic in nature and difficult to incorporate into hybrids. Differences in susceptibility to Fusarium ear rot among hybrids were investigated during the 1970's and earlier and attempts to breed for resistance to Fusarium ear rot were reported during the 1980's and 1990's. Although sources of resistance were identified, their genetic basis was not well understood and methods for evaluating hybrids were unsatisfactory. Since the mid-1990's nearly all the selection for Fusarium ear rot resistance in the United States has been conducted in the private sector. Understanding of the genetics of resistance has developed, and screening methods have improved, but they are still not completely satisfactory. Some public-sector resistance screening is still conducted (Clements et al., 2004) and these efforts have included identification of quantitative trait loci. The majority of university and USDA research related to fumonisins and F. verticillioides is directed at a basic understanding of the fungal-plant interactions. This research is likely to lead to novel resistance mechanisms in the future. In general, the level of resistance to Fusarium ear rot in commercial hybrids has improved over the past decade, and good levels of partial resistance are available.

Corn hybrid characteristics other than direct resistance to infection or mycotoxin development can contribute to mycotoxin management. Plants under stress are generally more susceptible to toxigenic fungi, and by planting locally adapted hybrids, the risk of abiotic stress on the plants can be reduced, also reducing the risk of mycotoxin contamination (CAST, 2003). Shelby et al (1994) reported fumonisin concentrations in a group of hybrids planted in 17 locations ranging from Georgia to Nebraska and Wisconsin. Hybrids grown outside their adapted range appeared to be more susceptible to fumonisin accumulation, and there was a negative correlation between fumonisins and latitude. Tolerance to specific environmental stresses, such as drought, has been suggested as a way to reduce vulnerability of corn hybrids to aflatoxins (Lisker and Lillehoj, 1991). Some ear and kernel characteristics of specific hybrids may provide physical barriers to ear rot infection. For example, kernels of some resistant hybrids have a thicker pericarp than that of susceptible hybrids. Hybrids with tight husk coverage tend to be less susceptible to Fusarium ear rot in California (Warfield and Davis, 1996), apparently due to the exclusion of thrips. Conversely, husk tightness can have a positive correlation with Gibberella ear rot vulnerability in the corn belt (Smith and White, 1988). In the central United States, tight husks can hinder the rate of grain drying, maintaining higher moisture contents favorable to Gibberella ear rot. Hybrids with ears that do not remain upright experience less ear rot. In the absence of known resistance genes or markers for resistance, it is likely that much of the selection for lower levels of ear rots and mycotoxins is a result of selection for ear and kernel traits that discourage fungal invasion indirectly or physically, rather than through a specific resistant reaction to the pathogen.

Recent research has focused on potential transgenic resistance against mycotoxigenic fungi or their toxins. Several such strategies toward reducing fumonisin contamination were reviewed by Duvick (2001). Three basic strategies are: 1) reducing infection by the pathogen, 2) inserting genes capable of degrading the toxin, or 3) reducing mycotoxin accumulation by interfering with the biosynthetic pathway. The first strategy could involve enhancing the expression of, or introducing novel genes to express, antifungal proteins or secondary metabolites, such as hydroxamic acids, phenolics, and stilbenes. Inducing existing plant defense pathways also might be effective in fending off infection. In regard to fumonisins, the greatest progress has been made with the second strategy, degradation. A fumonisin esterase gene and an amine oxidase gene from a yeast, Exophiala spinifera, capable of metabolizing fumonisins in vitro, have been identified and cloned. These genes have now been expressed in corn plants (Duvick, 2001). Fumonisin degradation is not expected to reduce infection or disease levels, because F. verticillioides transformants lacking fumonisin production are fully capable of causing ear rot. On the other hand, trichothecene mycotoxins such as DON are believed to be involved with pathogenicity of fungi such as F. graminearum. Therefore engineering plants for resistance to the toxins may protect them from disease as well. The third strategy could be pursued by engineering plants to produce proteins or compounds that interfere with mycotoxin biosynthesis, or alter the plant genome that it fails to produce signaling compounds that are involved in mycotoxin biosynthesis. The strategy of interfering with mycotoxin biosynthesis has been applied to both aflatoxins and trichothecenes. Biosynthesis of aflatoxins has been, and continues to be, a very active area of research with the goal of identifying targets for developing transgenic resistance. Biosynthesis of trichothecenes also has been studied for more than a decade, and many recent advances (e.g., McCormick et al., 1999) have led to the testing of transgenic wheat lines for Fusarium head blight resistance based on enzymatic degradation of trichothecene mycotoxins; similar approaches are being explored in corn (CAST, 2003). Biosynthesis of fumonisins has become better understood in recent years, and this knowledge undoubtedly will be exploited for transgenic control of fumonisins in the near future. Although many transgenic approaches for resistance to mycotoxin accumulation are being explored, implementation and commercialization of any resulting corn hybrids would face numerous challenges, technical, economic, and sociological.

Because of the relationship between insect injury and infection by Fusarium species, commercially available corn hybrids with transgenic insect protection (Bt hybrids) can be a tool for mycotoxin management. Control of various insect species in different parts of the world has been known to reduce ear rot occurrence for decades, but the unprecedented efficacy of transgenic insect protection can result in far more decisive reductions in Fusarium ear rot and fumonisins than previously possible. Bt corn hybrids consistently have been shown to have a much lower risk for fumonisin contamination than conventional hybrids. This has been demonstrated repeatedly in locations throughout the Corn Belt and in the southeastern U.S. (Munkvold et al, 1999; Hammond et al., 2004), as well as in other parts of the world De La Campa et al., 2005).

The efficacy of using Bt corn hybrids to indirectly reduce aflatoxin accumulation has been investigated, but reductions have been less consistent. Aflatoxin studies performed in the North Central states are unlikely to yield meaningful results because natural occurrence of significant levels of aflatoxins is uncommon, and artificial inoculation bypasses the potential protection afforded by Bt hybrids. Thus, studies in Iowa (Munkvold et al., 2000a) and Illinois (Maupin et al., 2001) have not demonstrated differences in aflatoxin between Bt and non-Bt hybrids. Studies in Texas and Mississippi (Williams et al., 2005), where natural A. flavus infection is common, have demonstrated reductions in aflatoxins in Bt hybrids. Aflatoxin occurrence is affected by insect injury, but other environmental factors, such as drought, may be more influential than insect injury. Therefore Bt hybrids may have relatively less influence on this mycotoxin. In addition, some insects that influence aflatoxin development (e.g., sap beetles and corn earworm) are not controlled by currently available transgenic hybrids.

Future prospects

Current management strategies in corn are reactive in relation to mycotoxin problems:

- Most producers, especially in the Corn Belt, do not use ear rot resistance as a criterion to choose hybrids
- Fields are managed to optimize yield vs. production costs, not to manage plant stress that can contribute to ear rot susceptibility
- Few fields are tested for mycotoxins prior to harvest
- The cost of grain drying is avoided when possible
- Mycotoxin problems are usually noted at the point of sale or when the grain is being fed to livestock, when options for managing the situation are limited

Therefore, usual outcomes of a mycotoxin problem include:

- Seeking alternative markets for contaminated grain, sometimes marketing at a reduced price
- Purchasing additional grain to substitute for the contaminated grain in livestock feed
- Destroying or discarding contaminated grain

In the future, a more proactive strategy can be envisioned, including:

- Wider use of partially resistant hybrids
- Wider use of insect-resistant transgenic hybrids
- Commercialization of hybrids with novel resistance sources, based on either native genes or transgenes
- Pre-harvest risk assessment:
    - Novel mycotoxin testing methods that are inexpensive and simple to use
    - Quantitative risk assessment modeling
- Grain cleaning and sorting methods that can separate contaminated kernels

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